

INTELLIGENT ACTIVE FORCE CONTROL
FOR MOBILE MANIPULATOR

ENDRA PITOWARNO

A thesis submitted in fulfilment of the
requirement for the award of the degree of
Doctor of Philosophy

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2006

ABSTRACT

This thesis presents a resolved acceleration control (RAC) and intelligent schemes of active force control (AFC) as approaches for the robust motion control of a mobile manipulator (MM) comprising a differentially driven wheeled mobile platform with a two-link planar arm mounted on top of the platform. The study emphasizes on the integrated kinematic and dynamic control strategy in which the RAC is used to manipulate the kinematic component while the intelligent schemes are implemented to compensate the dynamic effects including the bounded known/unknown disturbances and uncertainties. The proposed intelligent schemes are based on iterative learning control (ILC) and knowledge-based fuzzy (KBF) strategies. The effectiveness and robustness of the proposed schemes are investigated through a rigorous simulation study and later complemented with experimental results obtained through a number of experiments performed on a fully developed working prototype in a laboratory environment. A number of disturbances in the form of applied constant, vibratory and impact forces are deliberately introduced into the system to evaluate the system performances. The investigation clearly demonstrates the extreme robustness feature of the proposed control schemes compared to other systems considered in the study.

ABSTRAK

Tesis ini membincangkan suatu kaedah kawalan peleraian pecutan (RAC) dan kawalan pintar daya aktif (AFC) yang lasak terhadap sebuah robot pengolah mudah gerak (MM) melibatkan sebuah pelantar beroda yang dipacu secara pembezaan dan mudah alih bersama dengan sebuah pengolah lengan planar dua-sendai yang dipasang di atas pelantar. Kajian ini mengutamakan gabungan strategi kawalan kinematik dan dinamik yang mana RAC digunakan untuk mengolah komponen kinematik manakala skema AFC diterapkan untuk memampas kesan dinamik termasuk gangguan dan keadaan tak menentu. Skema pintar yang dicadangkan adalah berasaskan strategi kawalan pembelajaran berlelaran (ILC) dan kaedah logik kabur berasaskan pengetahuan. Kebolehan dan kelasakan skema yang dicadangkan dikaji dan diuji melalui kaedah simulasi dan seterusnya ditentusahkan melalui hasil eksperimen yang dibuat menggunakan sebuah prototaip robot pengolah mudah gerak yang dibina di dalam makmal. Sejumlah gangguan berupa daya malar, getaran dan dedenyut dikenakan kepada sistem robot untuk meneroka kebolehan dan keberkesanan sistem. Hasil simulasi dan eksperimen menunjukkan kelasakan dan keberkesanan skema kawalan yang dicadangkan berbanding dengan sistem lain.

TABLE OF CONTENTS

CHAPTER	SUBJECT	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xiv
	LIST OF FIGURES	xv
	LIST OF ABBREVIATIONS	xxiv
	LIST OF SYMBOLS	xxvi
	LIST OF APPENDICES	xxix
 1	 INTRODUCTION	
	1.1 General Introduction	1
	1.2 Research Background	3
	1.3 Problem Statements and Formulation	4
	1.4 Research Objectives	6
	1.5 Research Scope, Strategy and Methodology	7
	1.6 Research Contributions	10
	1.7 Organization of Thesis	11

THEORETICAL PRELIMINARIES AND REVIEW

2.1	Introduction	14
2.2	Mobile Manipulator System	14
2.2.1	Nonholonomic Mobile Robot System	15
2.2.2	Kinematic Modeling	17
2.2.3	Dynamic Modeling	20
2.2.4	Dynamics Modeling of the Manipulator Arm	24
2.3	Tracking Control of Nonholonomic Mobile Robot/Platform	26
2.4	Kinematic Control	26
2.5	Dynamic Control	29
2.6	Resolved Motion Rate Control and Resolved Acceleration Control	30
2.7	Force Control on Mobile Manipulator	33
2.7.1	Active Force Control in Robotic System	34
2.7.2	Estimation of the Inertia Matrix Based on Crude Approximation	36
2.7.3	Estimation of the Inertia Matrix Using Intelligent Schemes	37
2.8	Iterative Learning Control	38
2.9	Knowledge Based Fuzzy Control	43
2.9.1	Knowledge Based System	45
2.9.2	Fuzzy System	49
2.9.3	Knowledge Based Reasoning in Fuzzy System	50
2.10	Conclusion	51

3

**MOTION CONTROL OF MOBILE
MANIPULATOR USING RESOLVED
ACCELERATION CONTROL AND
ACTIVE FORCE CONTROL
(MM-RACAFC)**

3.1	Introduction	53
3.2	The Proposed MM-RACAFC Scheme	54
3.3	The Proposed RACAFC for Mobile Platform Section	60
3.4	Simulation	62
3.4.1	Simulation Parameters	62
3.4.2	Simulation Diagrams	67
3.5	Results and Discussion	75
3.5.1	DDMR with RACAFC	75
3.5.2	Mobile Manipulator Control	77
3.5.2.1	Simulation Procedure	78
3.5.2.2	Optimum K_p , K_d and IN	79
3.5.2.3	Effect of Constant Torque Disturbance, Q_c	80
3.5.2.4	Effect of Impact Disturbance, Q_{imp}	83
3.5.2.5	Effect of Vibration, Q_{vib}	85
3.6	Conclusion	87

4

**MOTION CONTROL OF MOBILE
MANIPULATOR USING RESOLVED
ACCELERATION CONTROL AND
PROPORTIONAL-INTEGRAL ACTIVE
FORCE CONTROL (MM-RACPIAFC)**

4.1	Introduction	88
-----	--------------	----

4.2	The Proposed MM-RACPIAFC Scheme	89
4.2.1	RAC Section	89
4.2.2	AFC Section	90
4.2.3	Proposed PIAFC Design	92
4.3	Simulation	93
4.4	Results and Discussion	96
4.4.1	Optimum K_p , K_d and IN_P and IN_I	97
4.4.2	Effects of Constant Torque Disturbance, Q_c	98
4.4.3	Effects of Impact Disturbance, Q_{imp}	100
4.4.4	Effects of Vibration, Q_{vib}	103
4.5	Conclusion	105

5

MOTION CONTROL OF MOBILE MANIPULATOR USING RESOLVED ACCELERATION CONTROL AND ITERATIVE LEARNING PROPORTIONAL-INTEGRAL ACTIVE FORCE CONTROL (MM-RACILPIAFC)

5.1	Introduction	106
5.2	Proposed MM-RACILAFC and MM-RACILPIAFC Schemes	107
5.2.1	RAC Section	107
5.2.2	MM-RACILAFC Design	108
5.2.3	MM-RACILPIAFC Design	110
5.3	Simulation	112
5.4	Results and Discussion	115
5.4.1	Optimum Φ and Γ for ILAFC	116
5.4.2	Optimum α and β for ILPIAFC	117

5.4.3 Effect of Constant Torque	
Disturbance, Q_c	117
5.4.4 Effect of Impact Disturbance,	
Q_{imp}	119
5.4.5 Effect of Vibration, Q_{vib}	121
5.5 Conclusion	123

6

MOTION CONTROL OF MOBILE MANIPULATOR USING RESOLVED ACCELERATION CONTROL AND KNOWLEDGE-BASED FUZZY ACTIVE FORCE CONTROL (MM-RACKBFAFC)

6.1 Introduction	124
6.2 The Proposed MM-RACKBFAFC	
Scheme	125
6.2.1 RAC Section	125
6.2.2 KBFAFC Section	126
6.2.3 Knowledge Investigation and	
Representation	128
6.2.4 Knowledge Acquisition and	
Processing	135
6.2.5 KBF Design	137
6.3 Simulation	139
6.4 Results and Discussion	141
6.4.1 Effect of Constant Torque	
Disturbance, Q_c	141
6.4.2 Effect of Impact Disturbance,	
Q_{imp}	142
6.4.3 Effect of Vibration, Q_{vib}	144
6.5 Conclusion	146

7 **COMPARATIVE STUDY OF THE AFC SCHEMES APPLIED TO MOBILE MANIPULATOR**

7.1	Introduction	147
7.2	Specifications of the AFC Schemes	148
7.3	Simulation	149
7.4	Results and Discussion	151
	7.4.1 Effect of Constant Torque Disturbance, Q_c	152
	7.4.2 Effect of Impact Disturbance, Q_{imp}	154
	7.4.3 Effect of Vibration, Q_{vib}	157
	7.4.4 Analysis of the Inertia Matrix	160
	7.4.5 Analysis of the Applied Motor Current and Torque	162
7.5	Conclusion	165

8 **EXPERIMENTAL STUDY OF THE MOBILE MANIPULATOR**

8.1	Introduction	166
8.2	Limitations and Specification of the Mobile Manipulator	167
8.3	PC-Based Controller	170
	8.3.1 Computer and Data Acquisition System (DAS) Card	171
	8.3.2 Frequency to Voltage Converter (f/V) Circuit	172
	8.3.3 Rotary Encoder Circuit using HCTL2000	173

8.3.4	Signal Conditioning Interfaces	175
8.3.5	Program Design	176
8.3.5.1	Program Flow Chart	176
8.3.5.2	Power System Calibration	
	Program Module	178
8.3.5.3	Program Modules	179
8.3.5.4	Real Time Monitor/Display	180
8.4	Embedded Controller using	
	Microcontroller PIC16F877	181
8.4.1	Circuit Diagram of the Embedded	
	Controller	183
8.4.2	Autonomous System and the	
	Controller Board	185
8.5	Experimental Results and Discussion	186
8.6	Conclusion	189

9

CONCLUSION AND RECOMMENDATIONS

9.1	Conclusion	190
9.2	Recommendations for Future Works	191

REFERENCES	193
-------------------	-----

APPENDICES	202
-------------------	-----

LIST OF TABLES

TABLE NO.	TITLE	PAGE
3.1	Mobile manipulator properties	64
3.2	Prescribed trajectory	65
3.3	Disturbances	65
3.4	Impact and vibration properties	66
3.5	Simulation methods and its parameters	67
4.1	TTEs of MM at vibrations for RACAFC and RACPIAFC schemes	104
6.1	The knowledge representation	134
6.2	The inference mechanism	135
7.1	Specifications of the AFC schemes	148
7.2	Average TTEs (in mm) for all the schemes at the arm, Q_c	153
7.3	Average TTEs (in mm) for all the schemes at the platform, Q_c	154
7.4	Average TTEs (in mm) for all the schemes at the arm, Q_{imp}	156
7.5	Average TTEs (in mm) for all the schemes at the platform, Q_{imp}	157
7.6	Average TTEs (in mm) for all the schemes at the arm, Q_{vib} .	159
7.7	Average TTEs (in mm) for all the schemes at the platform, Q_{vib} .	160
8.1	Specification of the MM rig	168

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	The research strategy in a flowchart	8
2.1	Mobile manipulator configuration in <i>XY Cartesian</i> coordinate system	15
2.2	An illustration of the RMRC schematic diagram	31
2.3	An illustration of the RMAC/RAC schematic diagram	32
2.4	AFC concept	35
2.5	RAC combined with AFC concept	36
2.6	P-type ILC	39
2.7	PD-type ILC	39
2.8	PI-type ILC	40
2.9	An illustration of a generic expert system	46
2.10	An illustration of KBS	47
2.11	An illustration of a fuzzy system	49
3.1	An outline of the RACAFC scheme	54
3.2	The proposed MM-RACAFC scheme	55
3.3	The MM-RAC scheme	55
3.4	The RAC controller	56
3.5	The proposed AFC controller	56
3.6	Schematic diagram of the proposed MM-RACAFC	58
3.7	The proposed AFC applied to the DDMR	61
3.8	DDMR trajectory	63
3.9	MM trajectory	63

3.10	Impact signals	66
3.11	Vibration signals	66
3.12	The Simulink diagram of DDMR-RACAFC	67
3.13	The Simulink diagram of MM-RAC	68
3.14	The Simulink diagram of MM-RACAFC	68
3.15	The Simulink diagram of the input functions for MM simulation	69
3.16	A Simulink diagram of the <i>Mobile Platform Input Function</i>	69
3.17	The Simulink diagram of the <i>Tip Position Input Function</i>	70
3.18	A Simulink diagram of the <i>RAC Controller and Inverse Kinematics Section</i>	70
3.19	A Simulink diagram of the <i>Inverse Kinematics</i> of the manipulator	71
3.20	A Simulink diagram of the <i>Inverse Kinematics</i> of the mobile platform	71
3.21	A Simulink diagram of <i>Direct Kinematics</i> of MM	72
3.22	A Simulink diagram of the <i>Direct Kinematics</i> of the manipulator	72
3.23	A Simulink diagram of the <i>Direct Kinematics</i> of the mobile platform	72
3.24	A Simulink diagram of the <i>Performance Display</i> section	73
3.25	A Simulink diagram of the <i>Inverse Dynamics</i> of MM	73
3.26	A Simulink diagram of the constraint matrix $M(q)$	74
3.27	A Simulink diagram of the manipulator's dynamics	74
3.28	Results of <i>IN</i> tuning (the white bar indicates the optimum value)	76
3.29a	TTE for case with no disturbances, RAC vs. RACAFC	76
3.29b	TTE for case with disturbances, RAC vs. RACAFC	76
3.30a	Robot animation for the RAC scheme	77
3.30b	Robot animation for the RACAFC scheme	77
3.31	A flow chart showing the simulation procedures	78
3.32a	TTE of arm, MM-RAC, Q_c	81

3.32b	TTE of arm, MM-RACAFC, Q_c	81
3.33a	TTE of platform, MM-RAC, Q_c	82
3.33b	TTE of platform, MM-RACAFC, Q_c	82
3.34	The dialog box of <i>External Disturbance Section</i>	83
3.35a	TTE of arm, MM-RAC at Q_{imp}	84
3.35b	TTE of arm, MM-RACAFC at Q_{imp}	84
3.36a	TTE of platform, MM-RAC at Q_{imp}	85
3.36b	TTE of platform, MM-RACAFC at Q_{imp}	85
3.37a	TTE of arm, MM-RAC at Q_{vib}	86
3.37b	TTE of arm, MM-RACAFC at Q_{vib}	86
3.38a	TTE of platform, MM-RAC at Q_{vib}	86
3.38b	TTE of platform, MM-RACAFC at Q_{vib}	86
4.1	The proposed MM-RACPIAFC	89
4.2	A schematic of the AFC loop	91
4.3	A Simulink model of the scheme with three control modes; RAC, RACAFC and proposed RACPIAFC	94
4.4a	A Simulink diagram of the PIAFC	94
4.4b	A Simulink diagram representing IN/K_m	95
4.4c	A Simulink diagram of the PI-IN	95
4.5a	TTE of arm, AFC/PIAFC, $Q_{ca} = [0.2;0.2;0.5;-0.5]$ Nm	98
4.5b	TTE of arm, AFC/PIAFC, $Q_{cb} = [2;2;5;-5]$ Nm	98
4.5c	TTE of arm, AFC/PIAFC, $Q_{cc} = [20;20;20;-20]$ Nm	99
4.5d	TTE of arm, AFC/PIAFC, $Q_{cd} = [30;30;30;-30]$ Nm	99
4.6a	TTE of platform, AFC/PIAFC, $Q_{ca} = [0.2;0.2;0.5;-0.5]$ Nm	100
4.6b	TTE of platform, AFC/PIAFC, $Q_{cb} = [2;2;5;-5]$ Nm	100
4.6c	TTE of platform, AFC/PIAFC, $Q_{cc} = [20;20;20;-20]$ Nm	100
4.6d	TTE of platform, AFC/PIAFC, $Q_{cd} = [30;30;30;-30]$ Nm	100
4.7a	TTE of arm, AFC/PIAFC, Q_{imp} , $Q_{gain} = 0.1$	101
4.7b	TTE of arm, AFC/PIAFC, Q_{imp} , $Q_{gain} = 0.5$	101
4.7c	TTE of arm, AFC/PIAFC, Q_{imp} , $Q_{gain} = 1$	101
4.7d	TTE of arm, AFC/PIAFC, Q_{imp} , $Q_{gain} = 3$	101
4.8a	TTE of platform, AFC/PIAFC, Q_{imp} , $Q_{gain} = 0.1$	102
4.8b	TTE of platform, AFC/PIAFC, Q_{imp} , $Q_{gain} = 0.5$	102

4.8c	TTE of platform, AFC/PIAFC, Q_{imp} , $Q_{gain} = 1$	102
4.8d	TTE of platform, AFC/PIAFC, Q_{imp} , $Q_{gain} = 3$	102
4.9a	TTE of arm, AFC/PIAFC, Q_{vib} , $Q_{gain} = 0.1$	103
4.9b	TTE of arm, AFC/PIAFC, Q_{vib} , $Q_{gain} = 0.5$	103
4.9c	TTE of arm, AFC/PIAFC, Q_{vib} , $Q_{gain} = 1$	103
4.9d	TTE of arm, AFC/PIAFC, Q_{vib} , $Q_{gain} = 3$	103
4.10a	TTE of platform, AFC/PIAFC, Q_{vib} , $Q_{gain} = 0.1$	104
4.10b	TTE of platform, AFC/PIAFC, Q_{vib} , $Q_{gain} = 0.5$	104
4.10c	TTE of platform, AFC/PIAFC, Q_{vib} , $Q_{gain} = 1$	105
4.10d	TTE of platform, AFC/PIAFC, Q_{vib} , $Q_{gain} = 3$	105
5.1	The proposed MM-RACILAFc	108
5.2	The proposed ILPIAFC	110
5.3	The Simulink diagram of the proposed MM-RACILAFc	112
5.4	The Simulink diagram of the proposed MM-RACILPIAFC	113
5.5a	The Simulink diagram of the block of ILAFc	113
5.5b	The Simulink diagram of the block ILC within the ILAFc	114
5.5c	The Simulink diagram of the block <i>State Space</i> within the ILC	114
5.6a	The Simulink diagram of the block LPIAFC	114
5.6b	The Simulink diagram of the block ILPI	115
5.7a	TTE of arm, 3 schemes, $Q_{ca} = [0.2;0.2;0.5;-0.5]$ Nm	118
5.7b	TTE of arm, 3 schemes, $Q_{cb} = [2;2;5;-5]$ Nm	118
5.7c	TTE of arm, 3 schemes, $Q_{cc} = [20;20;20;-20]$ Nm	118
5.7d	TTE of arm, 3 schemes, $Q_{cd} = [30;30;30;-30]$ Nm	118
5.8a	TTE of platform, 3 schemes, $Q_{ca} = [0.2;0.2;0.5;-0.5]$ Nm	119
5.8b	TTE of platform, 3 schemes, $Q_{cb} = [2;2;5;-5]$ Nm	119
5.8c	TTE of platform, 3 schemes, $Q_{cc} = [20;20;20;-20]$ Nm	119
5.8d	TTE of platform, 3 schemes, $Q_{cd} = [30;30;30;-30]$ Nm	119
5.9a	TTE of arm, 3 schemes, Q_{imp} , $Q_{gain} = 0.1$	120
5.9b	TTE of arm, 3 schemes, Q_{imp} , $Q_{gain} = 0.5$	120
5.9c	TTE of arm, 3 schemes, Q_{imp} , $Q_{gain} = 1$	120
5.9d	TTE of arm, 3 schemes, Q_{imp} , $Q_{gain} = 3$	120

5.10a	TTE of arm, 3 schemes, Q_{vib} , $Q_{gain} = 0.1$	121
5.10b	TTE of arm, 3 schemes, Q_{vib} , $Q_{gain} = 0.5$	121
5.10c	TTE of arm, 3 schemes, Q_{vib} , $Q_{gain} = 1$	121
5.10d	TTE of arm, 3 schemes, Q_{vib} , $Q_{gain} = 3$	121
5.11a	TTE of platform, 3 schemes, Q_{vib} , $Q_{gain} = 0.1$	122
5.11b	TTE of platform, 3 schemes, Q_{vib} , $Q_{gain} = 0.5$	122
5.11c	TTE of platform, 3 schemes, Q_{vib} , $Q_{gain} = 1$	122
5.11d	TTE of platform, 3 schemes, Q_{vib} , $Q_{gain} = 3$	122
6.1	The proposed MM-RACKBFAFC	125
6.2	An illustration of the global knowledge of mobile manipulators	128
6.3	The selected semantic networks of the MM's knowledge structure	129
6.4	The qualitative investigation in a semantic network	130
6.5a	Trajectory tracking of the mobile manipulator	131
6.5b	The track error at the tip end position for five cycles of repeating tasks in the simulation	131
6.5c	The track error at the tip end position for four cycles of repeating tasks in the experiment	131
6.6a	Angular velocity and TTE relationship for RACAFC with constant torque disturbance ($Q_{cc} = [20;20;-20;20]$ Nm)	133
6.6b	Angular velocity and TTE relationship for RACAFC with impact disturbance ($Q_{gain} = 1$)	133
6.6c	Angular velocity and TTE relationship for RACAFC with vibration ($Q_{gain} = 0.5$)	134
6.7a	Angular velocity signal as input of KBF for manipulator	136
6.7b	Expected IN signal as output of KBF for manipulator	136
6.7c	Angular velocity signal as input of KBF for platform	136
6.7d	Expected IN signal as output of KBF for platform	136
6.8a	MFs of input of joint-1 and joint-2	138
6.8b	MFs of output of joint-1 and joint-2	138

6.8c	MFs of input of wheel-L and wheel-R	138
6.8d	MFs of output of wheel-L and wheel-R	138
6.9	The Simulink diagram of the proposed MM-RACKBFAFC	139
6.10a	The Simulink diagram of the block of KBFAFC	140
6.10b	The Simulink diagram of the KBF System block	140
6.11a	TTE of arm, AFC/KBFAFC, $Q_{ca} = [2;2;5;-5]$ Nm	142
6.11b	TTE of arm, AFC/KBFAFC, $Q_{cb} = [30;30;30;-30]$ Nm	142
6.11c	TTE of platform, AFC/KBFAFC, $Q_{cc} = [2;2;5;-5]$ Nm	142
6.11d	TTE of platform, AFC/KBFAFC, $Q_{cd} = [30;30;30;-30]$ Nm	142
6.12a	TTE of arm, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 0.1$	143
6.12b	TTE of arm, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 0.5$	143
6.12c	TTE of arm, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 1$	143
6.12d	TTE of arm, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 3$	143
6.13a	TTE of platform, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 0.1$	144
6.13b	TTE of platform, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 0.5$	144
6.13c	TTE of platform, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 1$	144
6.13d	TTE of platform, AFC/KBFAFC, Q_{imp} , $Q_{gain} = 3$	144
6.14a	TTE of arm, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 0.1$	145
6.14b	TTE of arm, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 0.5$	145
6.14c	TTE of arm, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 1$	145
6.14d	TTE of arm, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 3$	145
6.15a	TTE of platform, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 0.1$	145
6.15b	TTE of platform, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 0.5$	145
6.15c	TTE of platform, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 1$	146
6.15d	TTE of platform, AFC/KBFAFC, Q_{vib} , $Q_{gain} = 3$	146
7.1	Simulink diagram of the master scheme involving all the five methods	149
7.2	A Simulink diagram showing the main mechanisms of the five AFC methods	149
7.3	The dialog box of the <i>AFC-PIAFC-ILAFc-ILPIAFC-KBFAFC</i> block	150
7.4	The dialog box of the <i>External Disturbances</i> block	151

7.5a	TTE of arm, all schemes, $Q_{ca} = [0.2; 0.2; 0.5; -0.5]$ Nm	152
7.5b	TTE of arm, all schemes, $Q_{cb} = [2; 2; 5; -5]$ Nm	152
7.5c	TTE of arm, all schemes, $Q_{cc} = [20; 20; 20; -20]$ Nm	152
7.5d	TTE of arm, all schemes, $Q_{cd} = [30; 30; 30; -30]$ Nm	152
7.6a	TTE of platform, all schemes, $Q_{ca} = [0.2; 0.2; 0.5; -0.5]$ Nm	153
7.6b	TTE of platform, all schemes, $Q_{cb} = [2; 2; 5; -5]$ Nm	153
7.6c	TTE of platform, all schemes, $Q_{cc} = [20; 20; 20; -20]$ Nm	154
7.6d	TTE of platform, all schemes, $Q_{cd} = [30; 30; 30; -30]$ Nm	154
7.7a	TTE of arm, all schemes, Q_{imp} , $Q_{gain} = 0.1$	155
7.7b	TTE of arm, all schemes, Q_{imp} , $Q_{gain} = 0.5$	155
7.7c	TTE of arm, all schemes, Q_{imp} , $Q_{gain} = 1$	155
7.7d	TTE of arm, all schemes, Q_{imp} , $Q_{gain} = 3$	155
7.8a	TTE of platform, all schemes, Q_{imp} , $Q_{gain} = 0.1$	156
7.8b	TTE of platform, all schemes, Q_{imp} , $Q_{gain} = 0.5$	156
7.8c	TTE of platform, all schemes, Q_{imp} , $Q_{gain} = 1$	156
7.8d	TTE of platform, all schemes, Q_{imp} , $Q_{gain} = 3$	156
7.9a	TTE of arm, all schemes, Q_{vib} , $Q_{gain} = 0.1$	158
7.9b	TTE of arm, all schemes, Q_{vib} , $Q_{gain} = 0.5$	158
7.9c	TTE of arm, all schemes, Q_{vib} , $Q_{gain} = 1$	158
7.9d	TTE of arm, all schemes, Q_{vib} , $Q_{gain} = 3$	158
7.10a	TTE of platform, all schemes, Q_{vib} , $Q_{gain} = 0.1$	159
7.10b	TTE of platform, all schemes, Q_{vib} , $Q_{gain} = 0.5$	159
7.10c	TTE of platform, all schemes, Q_{vib} , $Q_{gain} = 1$	159
7.10d	TTE of platform, all schemes, Q_{vib} , $Q_{gain} = 3$	159
7.11a	IN_1 (joint-1), 3 schemes, Q_{imp} , $Q_{gain} = 3$	161
7.11b	IN_2 (joint-2), 3 schemes, Q_{imp} , $Q_{gain} = 3$	161
7.11c	IN_L (wheel-L), 3 schemes, Q_{imp} , $Q_{gain} = 3$	161
7.11d	IN_R (wheel-R), 3 schemes, Q_{imp} , $Q_{gain} = 3$	161
7.12a	IN_1 (joint-1), 3 schemes, Q_{vib} , $Q_{gain} = 3$	162
7.12b	IN_2 (joint-2), 3 schemes, Q_{vib} , $Q_{gain} = 3$	162
7.12c	IN_L (wheel-L), 3 schemes, Q_{vib} , $Q_{gain} = 3$	162
7.12d	IN_R (wheel-R), 3 schemes, Q_{vib} , $Q_{gain} = 3$	162
7.13a	Ic_1 (joint-1), all schemes, Q_{imp} , $Q_{gain} = 3$	163

7.13b	Tq_1 (joint-1), all schemes, Q_{imp} , $Q_{gain} = 3$	163
7.13c	Ic_2 (joint-2), all schemes, Q_{imp} , $Q_{gain} = 3$	164
7.13d	Tq_1 (joint-2), all schemes, Q_{imp} , $Q_{gain} = 3$	164
7.13e	Ic_L (wheel-L), all schemes, Q_{imp} , $Q_{gain} = 3$	164
7.13f	Tq_L (wheel-L),all schemes, Q_{imp} , $Q_{gain} = 3$	164
7.13g	Ic_R (wheel-R), all schemes, Q_{imp} , $Q_{gain} = 3$	164
7.13h	Tq_R (wheel-R),all schemes, Q_{imp} , $Q_{gain} = 3$	164
8.1a	Isometric view of the mobile manipulator	169
8.1b	The complete experimental MM rig	169
8.1c	The improved gripper design	169
8.2	The experimental set-up for PC-based controller	170
8.3	Schematic diagram of the PC based controller	170
8.4	Two units of DAS1602 on the CPU Board	171
8.5	<i>Frequency to Voltage Converter</i> circuit	173
8.6	HCTL2000 based <i>Rotary Encoder Signal Conditioner</i>	174
8.7	Signal conditioning interface for the mobile platform	175
8.8	Signal conditioning interface for the manipulator	176
8.9	Flow chart of the PC-based program design	177
8.10	The display of the calibration process of the program MMH852.EXE	179
8.11	Program module <i>main()</i>	179
8.12	A Real Time Monitor display captured from the PC monitor	181
8.13	Specification of the autonomous mobile manipulator	182
8.14	Pins configuration of PIC16F877	183
8.15	Circuit diagram of PIC16F877 based controller	184
8.16a	Autonomous mobile manipulator	185
8.16b	The mounting of the embedded controller	185
8.16c	A close-up view of the PIC 16F877 based embedded controller	186
8.16d	Power supply unit for the embedded controller	186
8.17	Experimental results of the RACAFC scheme	187
8.18	Experimental results of the RACKBFAFC scheme	187

8.19	Tracking error of the arm for RACAFC and RACKBFAFC schemes during the experiment	188
8.20	Actual acceleration at the joints, RACAFC and RACKBFAFC	188
8.21	Actual current at motors of the joints, RACAFC and RACKBFAFC	188

LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
AFC	Active Force Control
AI	Artificial Intelligence
D	Derivative
DAC	Digital to Analog Converter
DDMR	Differentially Driven Mobile Robot
FS	Fuzzy System
I	Integral
IL	Iterative Learning
ILAFC	Iterative Learning Active Force Control
ILC	Iterative Learning Control
ILPI	Iterative Learning Proportional Integral
ILPIAFC	Iterative Learning Proportional Integral Active Force Control
KBF	Knowledge Based Fuzzy
KBFAFC	Knowledge Based Fuzzy Active Force Control
KBS	Knowledge Based System
MF	Membership of Function
MM	Mobile Manipulator
MMAFCON	Mobile Manipulator Active Force Control Online
P	Proportional
PC	Personal Computer
PD	Proportional Derivative
PI	Proportional Integral
PIAFC	Proportional Integral Active Force Control
PIC	Programmable Interface Controller

RAC	Resolved Acceleration Control
RACAFC	Resolved Acceleration Control - Active Force Control
RACIL AFC	Resolved Acceleration Control - Iterative Learning Active Force Control
RACILPIAFC	Resolved Acceleration Control - Iterative Learning Proportional Integral Active Force Control
RACKBFAFC	Resolved Acceleration Control - Knowledge Based Fuzzy Active Force Control
RACPIAFC	Resolved Acceleration Control - Proportional Integral Active Force Control
RMAC	Resolved Motion Acceleration Control
RMRC	Resolved Motion Rate Control
TTE	Trajectory Tracking Error

LIST OF SYMBOLS

SYMBOL	SUBJECT
α	Proportional constant of ILPIAFC scheme
$A(q)$	Constraint matrix
$B(q)$	Input transformation matrix
β	Integral constant of ILPIAFC scheme
b	Half width of the robot
$C(q, \dot{q})$	Centripetal and Coriolis matrix
d	the distance of point G to F of mobile manipulator
$F(q, \dot{q})$	Friction and gravitational vector
g	Acceleration due to gravity (m/s^2)
$G(s)$	A function in La place domain representing the feedforward gain in the AFC loop
$G_c(s)$	A function in La place domain representing the controller gain
$H(s)$	A function in Laplace domain representing the compensated gain in the AFC loop
h	Vector of the Coriolis and centrifugal torques
I	Inertia
I'	Estimated inertia
I_m	Motor current
I'_m	Measured motor current
I_c	Applied motor current
IN, \mathbf{IN}	Inertia matrix
IN'	Estimated inertia matrix

IN_F	Fixed IN
IN_I	Integral IN
IN_{IF}	Fixed integral IN
\mathbf{IN}_{IL}	Estimated inertia matrix from learning process
IN_{init}	Initial IN
IN_{IV}	Varied integral IN
IN_{KBF}	Knowledge-based fuzzy IN
IN_P	Proportional IN
IN_{PF}	Fixed proportional IN
IN_{PV}	Varied proportional IN
$IN_{RAC AFC}$	Fixed (crude) IN of RAC AFC scheme
J	Jacobian
K_p	Proportional constant
K_d	Derivative constant
$K_{pRAC AFC}$	Proportional constant for RAC AFC scheme
$K_{dRAC AFC}$	Derivative constant for RAC AFC scheme
K_m	Motor constant
$\lambda \in \Re^r$	Lagrange multiplier
Γ	Derivative constant for ILAFC scheme
$M(q)$	Symmetric and positive definite inertia matrix
m	Mass
Φ	Proportional constant for ILAFC scheme
Q	Bounded (known/unknown) disturbance
Q'	Measured disturbance
Q^*	Estimated disturbance
Q_c	Constant torque disturbance
Q_{ca}	Q_c of $[0.2 \ 0.2 \ 0.5 \ -0.5]^T$ Nm
Q_{cb}	Q_c of $[2 \ 2 \ 5 \ -5]^T$ Nm
Q_{cc}	Q_c of $[20 \ 20 \ 20 \ -20]^T$ Nm
Q_{cd}	Q_c of $[30 \ 30 \ 30 \ -30]^T$ Nm
Q_{gain}	Scaling factor for impact and vibration
Q_{imp}	Impact disturbance
Q_{vib}	Vibration disturbance

$q \in \mathbb{R}^p$	p generalized coordinate
r	radius of wheel
$S(q)$	Transformation matrix
θ	Angular position
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration
$\ddot{\theta}'$	Measured angular acceleration
θ_{ref}	Reference angular position
$\dot{\theta}_{ref}$	Reference angular velocity
$\ddot{\theta}_{ref}$	Reference angular acceleration
θ_{act}	Actual angular position
$\dot{\theta}_{act}$	Actual angular velocity
$\ddot{\theta}_{act}$	Actual angular acceleration
τ	Torque
T_q	Applied torque
φ	Heading angle of platform

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	LIST OF PUBLICATIONS	202
B	PROPERTIES OF MOBILE ANIPULATOR EQUATIONS	204
C	ACCELEROMETER ADXL 105	206
D	DC MOTOR VEXTA AXH SERIES	214
E	DATA ACQUISITION SYSTEM DAS 1602 CARD	221
F	LM2907 DATA SHEET	226
G	PIC16F877 DATA SHEET	232
H	LISTING PROGRAM MODULES	238

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Mobile manipulator is basically a conventional robotic arm mounted on a moving base. It is analogous to a human being with respect to the body and arm sections. He or she must control these parts integrally when performing a dynamic task to achieve the desired performance. As an example, a welder carrying out a welding operation needs to carry out the task by coordinating (control) simultaneously and continuously both the arm and body movements so that a favourable effect could be obtained from executing such task. It is indeed more challenging when human operators are replaced by robots or automated machines. Comprehensive analytical studies on the kinematics, dynamics and control aspects of the physical system should be carefully carried out in order to come up with an alternative system that produces results comparable with those of human operators.

The main subject of this thesis is the control of a mobile manipulator. As can be found in common industrial plants, robotic manipulators are conventionally bolted onto the floor, implying that the tasks involving a ground-fixed manipulator must be carefully configured within a limited volume of the workspace so that they (the tasks) can be executed in an efficient way. It is a well-known fact that the configuration is even more restrictive when a dextrous manipulation is required because the manipulator workspace is only a small part of the whole workspace.

Thus, attaching the manipulator onto a mobile platform offers the distinct advantages of dextrous manipulation and considerably larger workspace than the fixed-platform.

In recent years, there has been a great deal of interest in research on mobile manipulator (Yamamoto and Yun, 1996; Lin and Goldenberg, 2001; Umeda and Yakoh, 2002; and Tanner *et al.*, 2003). The study of mobile manipulator is mostly concentrated on the following main question: how to move, navigate or manoeuvre the system efficiently from one location to another in a structured or unstructured environment. The study normally focuses on two aspects, i.e., the kinematics and the dynamics of the system. Each has a different domain of analytical study with different goal setting, but the final or ultimate goal should be clearly defined in terms of the robot's capability to operate effectively within the specified workspace and environment with an additional feature – robustness, as a key factor in the development of the robotic system. The kinematic analysis is particularly useful to describe the robot's workspace and motion path planning tasks including obstacles avoidance, collision free moving capability and manoeuvrability, while the dynamic analysis deals with robustness in actual implementations.

Intelligent Active Force Control (AFC) combined with a resolved acceleration control (RAC) applied to the motion control of a mobile manipulator is the central theme of the proposed study. The work on AFC that was initiated by Hewit and Burdess (1981) can be regarded as one of the potentially robust force control schemes. A main feature of AFC is that the scheme is theoretically viable and can be practically implemented to the control of dynamical systems including robots (Hewit and Burdess, 1986, Hewit and Morris, 1996, Mailah, 1998). The AFC method involves a direct measurement of the acceleration and force quantities plus the appropriate estimation of the inertia (or mass) matrix to trigger its control strategy. The RAC part that was initially proposed by Luh *et al.* (1980) is a powerful acceleration mode control method that is still considered as one of the best control options due to its simplicity in real-time implementation. In the study, the RAC was designed as the basic kinematic controller while the AFC was applied as the dynamic counterpart.

1.2 Research Background

The study of motion control of mobile manipulators spans several different research domains and that it usually focuses on the kinematic and/or dynamic analyses. Research on kinematic analysis and dynamic analysis as two separate subjects have been extensively studied, but a study on integrating both the kinematics and dynamics is fairly new and relatively little research has been done.

In terms of its movement, a mobile manipulator can be classified as either holonomic or nonholonomic. The former can be simply described as one that can move in all directions without restriction. In classical mechanics, a nonholonomic system can be described as a rigid disk rolling on a horizontal plane without slippage (Goldstein, 1980) which in the control perspective is equivalent to a wheeled mobile robot driven by two wheels differentially. Theoretically, if a mechanical system exhibits certain symmetry properties, it is well known that there exist conserved quantities. If these conserved quantities are not integrable, then a class of nonholonomic systems is thereby obtained (Kolmanovsky, 1995). The kinematic control of mobile manipulators which the moving base subjects to these constraints had been widely investigated in the last decade, such as using Jacobian Transpose Control (Hootsmans *et al.*, 1992), adaptive stabilization (Colbaugh, 1998), genetic algorithm (Sakka and Chocron, 2001), repeatability analysis of Jacobian inverse kinematics (Tchon, 2002), readhesion control using external sensors (Umeda and Yakoh, 2002), and cooperative mobile manipulators (Tanner *et al.*, 2003). From the literatures reviewed, the kinematic control problem on mobile manipulators had been well established.

On the contrary, research that deals with both integrating kinematic and dynamic control is fairly new, especially on issue related to real-time implementation that directly involves computational costs and feasibility in hardware design. In this case, only a limited number of works can be found in the last decade, such as dynamics interaction (Yamamoto and Yun, 1996), and neural networks-based robust control (Lin and Goldenberg, 2001).

It is therefore proposed that the performed study dwells on the kinematic and dynamic control through the effective integration of RAC and AFC which is thought to be the main contribution of the thesis. The RAC deals with the kinematics while the AFC deals with the dynamics of the system. The RAC scheme is a powerful acceleration mode control method that could improve the performance of the existing conventional servo control as reported in a number of studies (Muir and Neuman, 1990; Kircanski and Kircanski, 1998; and Campa *et al.*, 2001). However, basically RAC is equivalent to a proportional-derivative control that cannot be classified as a robust control without additional robust control schemes. The AFC method has been rigorously studied by a number of researchers particularly in areas related to robotic control applications (Hewit and Burdett, 1981; Uchiyama, 1989; Hewit and Marouf, 1996; Mailah, 1998; and Kwek *et al.*, 2003). The AFC strategy is one of the practical force control methods that can be implemented in encountering the robot force control problems. The advantage of AFC method is that it has the ability to compensate the unpredictable external (and internal) forces effectively and reliably without rigorous mathematical computation. The capability of AFC method lies on how efficient the real-time inertia matrix of the robot could be estimated. Thus, the estimation technique of the inertia matrix is central to the implementation of the AFC strategy. More specifically, in the case of mobile manipulators, the AFC implementation has not been found in the literatures so that there exists possible research propositions that ought to be investigated and resolved particularly on the implementation of the AFC to the nonholonomic mobile manipulator system and the appropriate acquisition and estimation of the inertia matrix as duly described in the thesis.

1.3 Problem Statements and Formulation

In the study the RAC was developed as the integrated simplified mobile platform coordinate and heading angle, (x_v, y_v, φ) control and the *XY Cartesian* planar manipulator's tip position coordinate, (x_m, y_m) control. By using this RAC-based x , y , and heading angle control instead of the velocity and heading angle

control as suggested by Umeda and Yakoh (2002), the proposed control scheme would have a more flexible position, velocity and acceleration control. This flexibility is gained by the use of simultaneous input reference position, velocity and acceleration parameters. To tackle the robot's dynamic problem particularly those involving disturbances and uncertainties, the AFC schemes were incorporated into the control scheme. In general, the total control scheme was RACAFC.

An extension of an AFC by using an integral control to the existing pure (crude) AFC was proposed and investigated. Based on classical feedback control theories, by considering the fixed inertia matrix estimator as a proportional (P) term in the acceleration control mode, an integral (I) term can then be incorporated to the proportional control as a steady-state error refinement. The scheme was RACPIAFC.

As one of the proposed intelligent mechanisms, an iterative learning-based AFC was also designed, namely RACILAFC. The iterative learning method that was first introduced by Arimoto (1984) has been extensively developed by researchers in the case of robotics (Liang and Looze, 1993; Moon *et al.*, 1997; and Norrlof, 2002). The iterative learning method is known as one of the effective adaptation methods that can iteratively seek the optimum value of the control parameters. As an extension, a combination of the RACPIAFC and RACILAFC was also proposed, namely RACILPIAFC. In this case, the iterative learning procedure was used to optimise the proportional and integral parameters of the PIAFC.

A hybrid method namely Knowledge-Based Fuzzy (KBF) AFC was also proposed in the study. The concept of this scheme is to estimate the inertia matrix of the system using fuzzy logic (FL) system. The inference mechanism is based on a prior knowledge investigation of the system operations. For uncertain dynamic problems, it is usual to combine FL with online learning algorithms, such as Adaptive Network-based Fuzzy Inference System (Jang, 1993; Mar and Lin, 2001; and Hassanzadeh *et al.*, 2002). An example of knowledge-based fuzzy method applied to a feedback control can be found in Rhee *et al.* (1990). The KBF concept has mostly been found in system identification and data retrieval system, such as

dynamic voltage security (Tso *et al.*, 1996), classification and rule generation (Mitra *et al.*, 1997), heuristic learning-based KBF (Ouchi and Tazaki, 1998), and automatic model-based image segmentation system (Nanayakkara and Samarabandu, 2003). In this study, the KBFAFC was proposed as an alternative robust motion control of the mobile manipulator.

From the proposed schemes mentioned above, the problem formulation of the study can be summarised as follows:

1. In a continuous mobile manipulator motion with a continuous trajectory tracking the kinematic control should be integrated with the dynamic control effectively to perform the proper robust motion control. In this case, the combination of RAC and AFC scheme would satisfy the robustness requirements of the motion control.
2. In a continuous mobile manipulator operation with known/unknown disturbances the multiplication of the inertia matrix in the AFC scheme should be estimated correctly and in real-time due to the non-linear characteristics of the robot and its environment.
3. It is therefore necessary to implement the proper estimation techniques namely PIAFC, ILAFC, ILPIAFC, and KBFAFC.
4. An experimental investigation is then important to validate the feasibility for real implementation.

1.4 Research Objectives

The objectives of the research are as follows:

1. To investigate theoretically the feasibility of implementing the concept of proportional-integral (PI), IL, and KBF methods to the RACAFC

scheme applied to the mobile manipulator in the form of a detailed simulation study.

2. To evaluate the systems' performance in terms of its robustness and effectiveness.
3. To integrate the hardware and software in the form of an experimental mobile manipulator with the implementation of the proposed schemes.

1.5 Research Scope, Strategy and Methodology

The scope of the project encompasses both theoretical and experimental aspects of the proposed mobile manipulator control strategies. The study focused on the implementation of the RACPIAFC, RACIL AFC, RACILPIAFC, and RACKBFAFC in conjunction with the RACAFC scheme. These were applied to a mobile manipulator system comprising a nonholonomic differentially-driven wheeled mobile platform with a rigid two-link planar manipulator mounted on top of the platform that was assumed to operate horizontally. The theoretical framework involves the study of various underlying principles related to the AFC methods, kinematics and dynamics of the system, proportional-integral and iterative learning control, and knowledge-based fuzzy technique. This was transformed into a rigorous modelling and simulation study of the integrated schemes assuming a number of prescribed conditions and limitations. The performances of the proposed systems were evaluated and consequently compared to RAC and/or RACAFC counterparts for the purpose of benchmarking. The design and development of the hardware in the form of an experimental mobile manipulator was envisaged using mechatronics approach; integrating mobile manipulator with sensors and actuators via a PC-based controller. In addition, a simple embedded controller system based on Microchip IC PIC16F877 was implemented and introduced as a prototype to exhibit the practical implementation of the RACAFC scheme in the form of an autonomous mobile manipulator.

The proposed research strategy in the form of a flow chart is graphically shown in Figure 1.1.

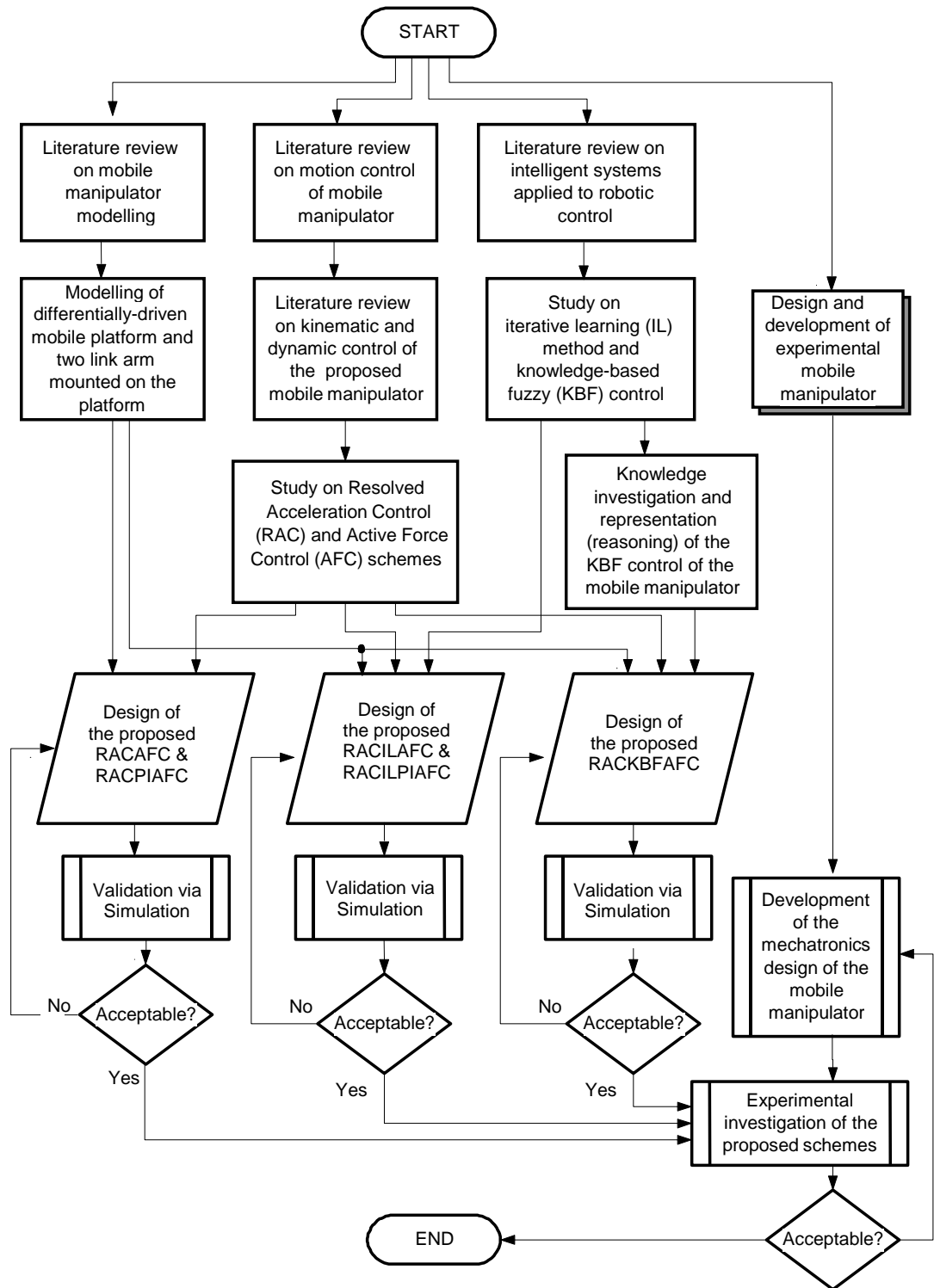


Figure 1.1: The research strategy in a flowchart.

From Figure 1.1, the research methodology pertaining to the project can be briefly described as follows:

1. Review literatures on areas of mobile manipulator robot, force control and intelligent control.
2. Study the AFC mechanism and related works applied to the control of mobile manipulator.
3. Identify the problems of the existing AFC strategies and other related issues involving concepts of proportional-integral, iterative learning, and knowledge-based fuzzy control.
4. Design and simulate the proposed basic RACAFC applied to the mobile manipulator.
5. Design and simulate the proposed extended RACAFC scheme in the form of RACPFAFC, RACILAF, and RACILPFAFC.
6. Test and evaluate the robustness of the schemes by introducing disturbances. Investigate the knowledge generated from these simulation studies.
7. Design and fully develop a laboratory scale mobile manipulator to verify the proposed methods. This includes the development of the hardware and software (C program), electronic interfacing devices, motors, sensors and mechanical mobile manipulator robot.
8. Perform an initial experimental investigation for the RAC and or RACAFC and investigate the knowledge from this experiment.
9. Design the fuzzy reasoning and inference mechanisms for the KBF method. A suitable database from the simulation and experimental study should be gathered for the decision making process.
10. Design the complete RACKBFAFC based on the previous knowledge investigation.

11. Simulate the proposed RACKBFAFC. Test and evaluate the robustness of the scheme by introducing disturbances.
12. Analyze the results and compare the system performances among the proposed methods.
13. Perform a series of experiments, analyze the results, discuss and compare them to those obtained theoretically.

1.6 Research Contributions

The main research contributions from this study are as follows:

1. New approximation methods that could make decision to compute continuously and on-line the appropriate inertia matrix of the mobile manipulator in order to improve the AFC strategy in the form of PIAFC, ILPIAFC, and KBFAFC.
2. New robust motion control schemes of the mobile manipulator in the form of the RACAFC, RACPIAFC, RACILAFC, RACILPIAFC, and RACKBFAFC.
3. A PC-based controlled laboratory-scaled mobile manipulator comprising a differentially-driven (wheeled) mobile robot/platform and a two-link planar manipulator mounted on top of the platform with a vertical gripper at the tip end position. This includes the development of the system hardware (electronic interfacing devices, motors, sensors and mechanical mobile manipulator) and software (a graphical real-time monitor & mobile manipulator online control in C program).
4. An autonomous mobile manipulator based on an embedded controller system.

1.7 Organization of Thesis

The thesis is organized into nine chapters. In Chapter 2, the fundamental concepts, underlying theories and reviews of the main topics of research pertaining to kinematic and dynamic control of mobile manipulator, RAC, AFC, iterative learning control and knowledge-based fuzzy are described. The basic principles of the well known RAC and the pure AFC method is first discussed with special attention focused on the method to enhance the strategy using intelligent means such as the use of neural network, fuzzy logic, and KBS (knowledge-based system) methods. The KBS inference mechanism, i.e. knowledge investigation and validation, knowledge representation, knowledge acquisition and knowledge processing are discussed as well as the KBS procedures. A preliminary discussion on the use of knowledge-based method to a fuzzy system is also addressed.

Chapter 3 describes a simulation study of the new proposed scheme of Resolved Acceleration Control combined with Active Force Control (RAC AFC) which employs a crude approximation on the inertia matrix estimation. This proposed scheme is considered as the basic robust motion control using AFC applied to the mobile manipulator that deals with the kinematics and dynamics as well. Based on this the new AFC based on a proportional-integral approach and the intelligent control using iterative learning and knowledge-based fuzzy could be developed and realized as presented in Chapters 3, 4 and 5. The tuning procedures of the inertia matrix estimator of the mobile platform are rigorously discussed in this chapter as well as for the manipulator. Some disturbances introduced to test the robustness of the proposed scheme are also described.

Chapter 4 presents a simulation study of the proposed extended version of the RACPIAFC (Resolved Acceleration Control and Proportional-Integral Active Force Control). This chapter provides a discussion on the advantages of using proportional and integral term to the existing AFC. Some results on the operation with disturbances are discussed by comparing the performances with pure AFC.

Chapter 5 discusses the next two proposed schemes, i.e., RACILAFc and RACILPIAFc. The first scheme incorporates a pure PD-type iterative learning control (ILC) to the AFC based on the tracking error. The second is a combination of the RACILAFc and RACPIAFc. The chapter provides alternative intelligent procedures applied to AFC, i.e. iterative learning, proportional-integral control, and the combination of both. A simulation study with the same parameters used in the previous scheme was performed.

Chapter 6 presents a simulation study of the main proposed scheme, i.e., Resolved Acceleration Control and Knowledge-Based Fuzzy Active Force Control (RACKBFAFc). The complete procedure to realize the knowledge-based fuzzy including the procedures of knowledge investigation, validation, representation, acquisition and processing is discussed. The procedure to investigate the knowledge is highlighted. As the most important part of knowledge based fuzzy, i.e., how the knowledge can be used as the reasoning mechanism to design the proper fuzzy output function is then described. This chapter also presents the complete results of the simulation study subjected to several conditions of the kinematic and dynamic aspects including some disturbances effect.

Chapter 7 discusses a comparative study of the RACAFc, RACPIAFc, RACILAFc, RACILPIAFc, and RACKBFAFc. The comparison is mainly focused on the generated track errors signal patterns, the computed estimated inertia matrix and the applied starting current and torques due to a number of varied external disturbances.

Chapter 8 describes the design and development of the experimental mobile manipulator (a differentially driven mobile robot/platform with a two-link planar robot arm mounted on the top of the platform) with graphical and real-time monitor control-programming feature. This chapter also provides a programming and experimental procedure based on the RAC and RACAFc schemes.

Finally, Chapter 9 concludes the research project. The directions and recommendations for future research works are also outlined. A list of publications

related to the study and some of the specifications and datasheet of components used for developing the experimental mobile manipulator are enclosed in the appendices.

REFERENCES

- Arimoto, S. (1984). Bettering Operation of Dynamic Systems by Learning: A New Control Theory for Servomechanism and Mechatronics Systems. *Proc. 23rd IEEE CDC*: Las Vegas.
- Arimoto, S. (1990). Robustness of Learning Control for Robot Manipulators. *Proc. IEEE Int'l Conf. on Robotics and Automation*. 1528-1533.
- Arimoto, S., Kawamura, S., and Miyazaki, F. (1984). Bettering operation for robots by learning. *Journal of Robotic Systems*. **1**. 123-140.
- Avrachenkov, K. E. (1998). Iterative learning control based on quasi-Newton methods. *Proc. 37th IEEE Conf. Decision & Control*. 170-174.
- Bayle, B., Fourquet, J. Y. and Renaud, M. (2001). Manipulability Analysis for Mobile Manipulators. *Proc. IEEE Int'l Conf. on Robotics & Automation*. 1251-1256.
- Bukkems, B., Kostic, D, Jager, B., and Steinbuch, M. (2005). Learning-Based Identification and Iterative Learning Control of Direct-Drive Robots. *IEEE Trans. Control Systems Technology*. **13**(4). 537-549.
- Campa, R., Kelly, R., and Garcia, E. (2001). On Stability of the Resolved Acceleration Control. *Proc. IEEE International Conf. on Robotics & Automation*. 3523-3528.
- Chen, Y., Wen, C., Xu, J. X., and Sun, M. (1998). High-Order Iterative Learning Identification of Projectile's Aerodynamic Drag Coefficient Curve from Radar Measured Velocity Data. *IEEE Trans. Control Systems Technology*. **6**(4). 563-570.
- Ciliz, M. K. (2005). Rule base Reduction for Knowledge0based Fuzzy Controllers with Application to a Vacuum Cleaner. *Journal of Expert Systems with Applications*. **20**. 175-184.

- Colbaugh, R. (1998). Adaptive Stabilization of Mobile Manipulator. *Proc. American Control Conf.* 1-5.
- Computer Boards, Inc. (Ed.)(1998). *CIO-DAS1602/12, CIO-DAS1601/12, CIO-DAS1602/16 Standard and -P5 versions. Revision 4.* Computer Boards, Inc.
- D'souza, A., Vijayakumar, S., and Schaal, S. (2001). Learning inverse Kinematics. *Proc. IEEE/RSJ Int'l Conf. Intelligent Robots and Systems.* 298-303.
- Elci, H., Longman, R. W., Phan, M. Q., Juang, J. N., and Ugoletti, R. (2002). Simple Learning Control Made Practical by Zero-Phase Filtering: Applications to Robotics. *IEEE Trans. Circuits and Systems – I: Fundamental Theory and Applications.* **49**(6). 753-767.
- Fierro, R. and Lewis, F. L. (1995).Control of Nonholonomic Mobile Robot: Backstepping Kinematics into Dynamics. *Proc. 34th Conf. On Decision and Control.* 3805-3810.
- Fierro, R. and Lewis, F. L. (1998). Control of Nonholonomic Mobile Robot Using Neural Networks. *IEEE Trans. Neural Networks.* **6**(4). 589-600.
- Franklin, G., Powell, F., David, J. and Naeini, A. E. (2002). *Feedback Control of Dynamic Systems – 4rd Ed.* New Jersey: Prentice – Hall, Inc.
- Fu, K.S., Gonzales, R.C. and Lee, C.S.G. (1987). *Robotics: Control, Sensing, Vision, and Intelligence.* New York: McGraw-Hill, Inc.
- Fukao, T., Nakagawa, H., and Adachi, N. (2000). Adaptive Tracking Control of a Nonholonomic Mobile Robot. *IEEE Trans. Robotic and Automation.* **16**(5). 609-615.
- Godler, I., Honda, H., and Ohnishi, K. (2002). Design Guidelines for Disturbance Observer's Filter in Discrete Time. *Proc. International Workshop on Advanced Motion Control.* **1.** 390-395.
- Godler, I., Inoue, M., Ninomiya, T., and Yamashita, T. (1999). Robustness Comparison of Control Schemes with Disturbance Observer and with Acceleration Control Loop. *Proc. IEEE ISIE.* 1035-1040.
- Goldstein, H. (1980). *Classical Mechanics.* New York: Addison-Wesley.

- Growe, S., Schröder, T., and Liedtke, C.Ë. (2000). Use of Bayesian Networks as Judgement Calculus in a Knowledge-Based Image Interpretation System. *IAPRS Journal*. **33**.101-110.
- Hamamoto, K. and Sugie, T. (2002). Iterative Learning Control for Robot Manipulators Using the Finite Dimensional Input Subspace. *IEEE Trans. Robotics and Automation*. **18**(4). 632-635.
- Hassanzadeh, I., Khanmohammadi, S., Jiang, J., and Alizadeh, G. (2002). Implementation of a Functional Link-net ANFIS Controller for a Robot Manipulator. *Proc. Int'l Workshop on Robotic Motion and Control*. 399-404.
- Hewit, J. R. and Burdess, J. S. (1981). Fast Dynamic Decoupled Control for Robotics Using Active Force Control. *Trans. Mechanism and Machine Theory*. **16**(5). 535-542.
- Hewit, J. R. and Marouf, K. B. (1996). Practical Control Enhancement via Mechatronics Design. *IEEE Trans. Industrial Electronics*. **43**(1). 16-22.
- Hewit, J.R. and Burdess, J. S. (1986). An Active Method for the Control of Mechanical Systems in The Presence of Unmeasurable Forcing. *Trans. Mechanism and Machine Theory*. **21**(3). 393-400.
- Hewit, J.R. and Morris, J. R. (1999). Disturbance Observation Control with Estimation of The Inertia Matrix. *Proc. IEEE/ASME, International Conference on Advanced Intelligent Mechatronics*. 753-757.
- Hildebrand, L. and Fathi, M. (2004). Knowledge-Based Fuzzy Color Processing. *IEEE Trans. Systems, Man, and Cybernetics – Part C: Applications and Reviews*. **34**(4). 499-505.
- Hootsmans, N. A. M., Dubowsky, S., Mo, P. (1992). The Experimental Performance of a Mobile Manipulator Control Algorithm. *Proc. IEEE Int'l Conf. on Robotic and Automation*. 1948-1954.
- Ignizio, J. P. (1991). *Introduction To Expert Systems: The Development and Implementation of Rule-Based Expert System*. Singapore: McGraw-Hill, Inc.
- Jang, J. S. R. (1993). ANFIS: Adaptive Network-Based Fuzzy Inference System. *IEEE Trans. Systems, Man, and Cybernetics*. **23**(3). 665-685.

- Kanayama, Y., Kimura, Y., Miyazaki, F., and Noguchi, T. (1990). A Stable Tracking Control Method for an Autonomous Mobile Robot. *Proc. IEEE Int. Conf. Robot and Automation*. 384-389.
- Kim, S. W. and Lee, J. J. (1993). Resolved Motion Rate Control of Redundant Robots using Fuzzy Logic. *Proc. 2nd IEEE Int'l Conf. Fuzzy Systems*. **1**. 333-338.
- Kircanski, M. and Kircanski, N. (1998)'' Resolved rate and acceleration control in the presence of actuator constraints. *IEEE Control Systems Magazine*. **18**(1). 42-47.
- Kircanski, M., Kircanski, N., Lekovic, D., and Vukobratovic, M. (1994)'' An Experimental Study of Resolved Acceleration Control in Singularities: Damped Least-Squares Approach. *Proc. IEEE Int'l Conf. Robotics and Automation*. **4**. 2686-2691.
- Kolmanovsky, I. and McClamroch, N. H. (1995). Development in Nonholonomic Control Problems. *IEEE Control Systems*. 20-36.
- Komada, S. and Ohnishi, K. (1990). Force Feedback Control of Robot Manipulator by the Acceleration Tracing Orientation Method. *IEEE Trans. Industrial Electronics*. **37**(1). 6-12.
- Komada, S., Kimura, T., Ishida, M., and Hori, T. (1996). Robust Position Control of Manipulator based on Disturbance Observer and Inertia Identifier in Task Space. *Proc. International Workshop on Advanced Motion Control*. **1**. 225-230.
- Kreutz, K. (1989). On Manipulator Control by Exact Linearization. *IEEE Trans. Automatic Control*. **34**(7). 763-767.
- Kuwata, Y. and Yatsu, M. (1997). Managing Knowledge using a Semantic Network. *Proc. AAAI Spring Symposium: Artificial Intelligence in Knowledge Management*. 94-98.
- Kwek, L. C., Wong, E. K., Loo, C. K. and Rao, M. V. C. (2003). Application of Active Force Control and Iterative Learning in a 5-Link Biped Robot. *Journal of Intelligent and Robotic Systems*. **37**. 143-162.

- Lewis, F. L. and Jagannathan, S. (1999). *Neural Network Control of Robot Manipulators and Nonlinear Systems*. London: Taylor & Francis.
- Liang, Y. J. and Looze, D. P. (1993). Performances and Robustness Issues in Iterative Learning Control. *Proc. 32nd Conf. Decision and Control*. 1990-1995.
- Liao, S. H. (2005). Expert System Methodologies and Applications – a Decade Review from 1995 to 2004. *Journal of Expert System with Applications*. **28**. 93-103.
- Lin, S. (2001). *Robust and Intelligent Control of Mobile Manipulators*. University of Toronto: PhD Thesis.
- Lin, S. and Goldenberg, A. A. (2001). Neural-Network Control of Mobile Manipulator. *IEEE Trans. Neural Networks*. **12**(5). 1121-1133.
- Luh, J. Y. S., Walker, M. W., and Paul, R. P. C. (1980). Resolved-Acceleration Control of Mechanical Manipulator. *IEEE Trans. Automatic Control*. **25**. 486-474.
- Mailah, M. (1998). *Intelligent Active Force Control of a Rigid Robot Arm Using Neural Network and Iterative Learning Algorithms*. University of Dundee, UK: Ph.D Thesis.
- Mailah, M. and Chong, J. (2002). Control of A Robot Arm Using Iterative Learning Control with A Stopping Criterion. *Jurnal Teknologi, UTM*. **37**. 55-72.
- Mailah, M. and Hooi, N. B. (2000). Intelligent Active Force Control of a Three-Link Manipulator Using Iterative Learning Technique. *Jurnal Teknologi, UTM*. **A**. 46-69.
- Mailah, M. and Rahim, N. I. A. (2000). Intelligent Active Force Control of a Robot Arm Using Fuzzy Logic. *Proc. IEEE International Conference on Intelligent Systems and Technologies TENCON 2000*, Kuala Lumpur. **2**. 291-297.
- Mailah, M. and Yong, O. M. (2001). Intelligent Adaptive Active Force Control of A Robot Arm With Embedded Iterative Learning Algorithms. *Jurnal Teknologi, UTM*. **35**(A). 85-98.
- Mailah, M., Yee, W. M. and Jamaluddin, H. (2002). Intelligent Active Force Control A Robot Arm Using Genetic Algorithm. *Jurnal Mekanikal, Faculty of Mechanical Engineering, UTM*. **13**. 50-63.

- Mar, J. and Lin, F. J. (2001). An ANFIS Controller for the Car-Following Collision Prevention System. *IEEE Trans. Vehicular Technology*. **50**(4). 1106-1113.
- Marakas, G. M. (1999). *Decision Support Systems in The Twenty-First Century*. New Jersey: Prentice Hall.
- Mitchell, T. (1997). *Machine Learning*. New York: McGraw Hill.
- Mitra, S., De, R. K., and Pal, S. K. (1997). Knowledge-Based Fuzzy MLP for Classification and Rule Generation. *IEEE Trans. Neural Networks*. **8**(6). 1338-1350.
- Mohri, A., Furuno, S., Iwamura, M. and Yamamoto, M. (2001). Sub-Optimal Trajectory Planning of Mobile Manipulator. *Proc. IEEE Int'l Conf. on Robotics & Automation*. 1271-1276.
- Moon, J. H., Doh, T. Y., and Chung, M. J. (1997). An Iterative Learning Control Scheme for Manipulators. *Proc. IEEE IROS*. 759-765.
- Muir, P. F. and Neuman, C. P. (1990). Resolved Motion Rate and Resolved Acceleration Servocontrol of Wheeled Mobile Robots. *Proc. IEEE Int'l Conf. Robotics and Automation*. **2**. 1133-1140.
- Nanayakkara, N. D. and Samarabandu, J. (2003). Unsupervised Model Based Image Segmentation Using Domain Knowledge-Based Fuzzy Logic and Edge Enhancement. *Proc. ICME*. 577-580.
- Negnevitsky, M. (2002). *Artificial Intelligence – A Guide to Intelligent Systems*. London: Addison-Wesley.
- Norrlof, M. (2002). An Adaptive Iterative Learning Control Algorithm with Experiment on an Industrial Robot. *IEEE Trans. Robotic and Automation*. **18**(2). 245-251.
- O'neil, K. A., Chen, Y. C., and Seng, J. (1997). Removing Singularities of Resolved Motion Rate Control of Mechanism, including Self-Motion. *IEEE Trans. Robotics and Automation*. **13**(5). 741-751.
- Ouchi, Y. and Tazaki, E. (1998). Heuristic Approach to Topology Generation for Knowledge based Fuzzy Petri Nets. *Proc. 2nd Int'l Conf. Knowledge-Based Intelligent Electronics System*. 331-334.

- Panditt, M. and Buchheit, K. H. (1999). Optimizing Iterative Learning Control of Cyclic Production Processes with Application to Extruders. *IEEE Trans. Control Systems Technology*. **7**(3). 382-390.
- Papadopoulos, E. and Poulakakis, I. (2001). Planning and Obstacle Avoidance for Mobile Robots. *Proc. IEEE Int'l Conf. Robotics and Automation*. 3967-3972.
- Papadopoulos, E. and Poulakakis, J. (2000). Planning and Model-based Control for Mobile Manipulators. *Proc. IEEE/RSJ International Conf. on Int'l Robots and Systems*. **3**. 1810-1815.
- Perrier, C., Dauchez, P. and Pierrot, F. (1998). A Global Approach for Motion Generation of Non-Holonomic Mobile Manipulator. *Proc. IEEE Int'l Conf. on Robotic & Automation*. 2971-2976.
- Pin, F. G. and Killough, S. M. (1994). A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots. *IEEE Trans. Robotics and Automation*. **10**(4). 480-489.
- Pitowarno, E., Musa Mailah and Hishamuddin Jamaluddin. (2001). Trajectory Error Pattern Refinement of A Robot Control Scheme Using A Knowledge-Based Method. *Proc. (in a CDRom) International Conference on Information, Communications & Signal Processing (ICICS 2001)*. Singapore. P0301.
- Pitowarno, E., Mailah, M., and Jamaluddin, H. (2002). Knowledge-Based Trajectory Error Pattern Method Applied to an Active Force Control Scheme. *IJUM Engineering Journal*. **3**(1). 1-15.
- Pourboghtrati, F. (2002). Exponential Stabilization of Nonholonomic Mobile Robot. *Computer and Electrical Engineering*. **28**. 349-359.
- Rhee, F. V. D., Lemke, H. R. V. N., and Duckman, J. G. (1990). Knowledge Based Fuzzy Control of System. *IEEE Trans. Automatic Control*. **35**(2). 148-155.
- Saha, S. K., Angeles, J., and Darcovic, J. (1995). The Design of Kinematically Isotropic Rolling Robots with Omnidirectional Wheels. *Journal of Mechanics and Machines Theory*. **30**(8). 1127-1137.
- Sakka, S. and Chocron, O. (2001). Optimal Design and Configurations of A Mobile Manipulator using Genetic Algorithms. *Proc. 10th IEEE International Workshop on Robot and Human Interactive Communication*. 268-273.

- Shibata, K., Murakami, T., and Ohnishi, K. (1995). Control of A Mobile Manipulator Based on Equivalent Mass Matrix. *Proc. IEEE 21st International Conference on Industrial Electronics, Control, and Instrumentation*. **2**. 1330-1335.
- Soucek, B. (1989). *Neural and Concurrent Real-Time Systems: The Sixth Generation*. New York: John Wiley & Sons, Inc.
- Sugar, T. G. and Kumar, V. (2002). Control of Cooperating Mobile Manipulators. *IEEE Trans. Robotic and Automation*. **18**(1). 94-103.
- Tamas, K. N., Andrea, R. D., and Ganguly, P. (2004). Near-optimal Dynamic Trajectory Generation and Control of an Omnidirectional Vehicle. *Journal of Robotics and Autonomous Systems*. **46**. 47-64.
- Tanner, H. G. (2003). Nonholonomic Navigation and Control of Cooperating Mobile Manipulators. *IEEE Trans. Robotic and Automation*. **19**(1). 53-61.
- Tchon, K. (2002). Repeatability of Inverse Kinematics Algorithms for Mobile Manipulator. *IEEE Trans. Automatic Control*. **47**(8). 1376-1380.
- Tsai, C. H., Wang, C. H., and Lin, W. S. (2000). Robust Fuzzy Model-Following Control of Robot Manipulator. *IEEE Trans. Fuzzy Systems*. **8**(4). 462-469.
- Tso, S. K., Zhu, T. X., Zeng, Q. Y., and Lo, K. L. (1996). Fuzzy Reasoning for Knowledge Assessment of Dynamic Voltage Security. *IEEE Proc. Gener. Transm. Distrib.* **143**(2). 157-162.
- Uchiyama, M. (1989). Control of Robot Arms. *Trans. Japan Society of Mechanical Engineers*. III. **32**(1). 1-9.
- Umeda, Y. and Yakoh, T. (2002). Configuration and Readhesion Control for a Mobile Robot With External Sensor. *IEEE Trans. Industrial Electronics*. **49**(1). 241-247.
- Verwoerd, M. H. A. (2005). *Iterative Learning Control, a Critical Review*. University of Twente, Netherlands: Ph.D Thesis.
- Wang, C. C. and Kumar, V. (1993). Velocity Control of Mobile Manipulators. *Proc. IEEE Int'l Conf. on Robotics and Automation*. **2**. 713-718.

- Yamamoto, Y. and Yun, X. (1996). Effect of the Dynamics Interaction on Coordinated Control of Mobile Manipulators. *IEEE Trans. Robotic and Automation*. **12**(5). 816-824.
- Yasuda, G. and Takai, H. (2001). Sensor-Based Path Planning and Intelligent Steering Control of Nonholonomic Mobile Robot. *Proc. 27th Annual Conf. IEEE Industrial Electronics Society, IECON*. 317-322.
- Young-Tack, P., and Wilkins, D. C. (1992). Representation and Control of Knowledge-Bases for Support of Multiple Task. *Proc. IEEE Conf. in Artificial Intelligence for Applications*. Monterey, CA.
- Zadeh, L. A. (1988). Fuzzy Logic. *IEEE Computer*. 83-93.
- Zadeh, L. A. (1996). Fuzzy Logic = Computing with Words. *IEEE Trans. Fuzzy Systems*. **4**(2). 103-111.